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# ACOUSTIC DYNAMICS OF A SWIRL PREMIXED COMBUSTOR WITH DIFFERENT OPERATING CONDITIONS

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**Abstract**

The effects of inlet swirl and external excitation on the flow field and combustion acoustic modes in a low NOx premixed combustor are experimentally investigated using a 100kW laboratory rig. It combines different operating conditions with variations in swirl number and varying levels of external excitation which are critical factors influencing the flow- flame interaction within the combustor. Results show the formation of a vortex induced central recirculation zone (CRZ) for the two swirl conditions which increase in length and width with changes in the swirl strength and forcing. The flow structure eventually merges with the high momentum flow region, a feature common to many swirl combustors. The acoustic oscillations were observed to be affected by the variations in the swirl strength with further dynamics at different levels of excitation. Accurate combination of these conditions (swirl, and excitation) could be advantageous in suppressing the intensity of the destructive acoustic instabilities in the burner. Results of this nature provide information for the design of an active control system for the combustor.


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*Keywords:* Acoustic modes, Swirl Number, Injection, excitation.

## 1. Introduction

Combustion instabilities is a major challenge of gas turbine combustors, especially when operated at low NOx conditions. These instabilities are combustion driven, self-excited, occur at discrete frequencies and are highly influenced by the combustor's natural frequency [1, 2]. They generate high amplitude oscillations capable of damaging the system and limiting its operating conditions. Combustion instabilities are caused by the coupling between unsteady heat release and the dynamic pressure of the combustor. When both are in phase, and the rate of acoustic growth is

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higher than the acoustic damping rate [3, 4, 5]. The variation in this phase angle is linked to many factors, such as flow and flame dynamics as well as the geometry of the combustor. This coupling of the combustor acoustic with the reactive mixture is affected by the pressure drop at the injector as a result of the flow separation and rapid expansion of the flame holder. The vortex shedding in the swirling flow produces large scale coherent vortical structures [7] which are convected to the flame, resulting in the distortion of the flame front and the oscillation of heat release. These mechanisms lead to fluctuations in the time scales of the combustion system which are linked to combustion instabilities, expressed thus;

$$\boldsymbol{\tau_{conv}} + \boldsymbol{\tau_{chem}} = \mathbf{KT} \tag{1}$$

where $\boldsymbol{\tau_{conv}}$ denotes the convective time delay, (the time required for the equivalence ratio perturbation or vortex shedding to convect from its formation point to the center of mass of the flame) and $\boldsymbol{\tau_{chem}}$ denotes the chemical time delay, while T and K denote acoustic period and a constant related to the combustor chamber acoustics, respectively[7, 8].

Swirling flows are used in a gas turbine to anchor and stabilise the flame of low NOx combustion. Vortex breakdown in the flow creates many flow structures such as the recirculation zones, precessing vortex core and shear layers [9,10]. The central recirculation zone mixes the hot combustibles gases with the inlet cold flow and stabilizes the flame. The CRZ is displaced from the central axis with the formation of high momentum flow regions within the shear layer. As the vortex breakdown disrupts the flow symmetry, the vortex core precesses around the combustor axis of symmetry [6,11]. These structures enhance flow mixing and flame stabilization. However, they are convected to the flame zone, where they interact with the flame resulting in the wrinkling of the flame front thus oscillating the heat release. Therefore, the flow field plays an important role in combustion instabilities, as reported in many published works. Broda [12] experimentally investigated the combustion dynamics of a swirl combustor and showed that the instability amplitude is reduced with an increase in swirl number. Wang et al [13, 9] examined the evolution of vortical flow structures with variations in swirl strength. Tangirala et al [14] investigated the effect of swirl and heat release on the flow and flame dynamics. It was shown that by increasing the swirl number up to a certain value approximately unity, the mixing and flame stability was improved and further increase in swirl number reduces the turbulence level and flame stability. The effect of excitation of the swirling flame has also been reported. Palies et al [15] investigated longitudinal forced swirl flames and demonstrated that there were two distinct velocity mechanisms which influence the flame response. The first was the direct forcing of the flame by the signal, where a swirl was not used. The second was the flame response to the acoustic propagation through the swirl excitation resulting in the oscillation of flame angle, an important factor which influences flame dynamics. This periodicity is convected to the flame with an effect of heat release oscillations which drives instabilities.

However, the evolution of the flow structures at various excitation levels and its corresponding effects on the flame dynamics is yet to be fully understood. Some studies have even suggested that the interaction between the PVC and the forcing frequencies could raise further disturbance on both the flow and flame fields[16]. In view of these, this study seeks to investigate the influence of swirl strength and external excitation on the flow field and its corresponding effects on the flame – acoustic dynamics using a more realistic real time approach. This is aimed at obtaining an operating condition which guarantees an optimal acoustic level for a stable and efficient running condition of the system.

## 2. Experimental Setup and Procedure

A 100kW acoustically excited swirl-stabilized burner (figure 1) was used for this study. At the bottom of the 102-mm internal diameter plenum, a WS13E – 8 Ohm Visaton loud speaker is positioned for the excitation of the fuel – air mixture. At 110mm above the loudspeaker's diaphragm are two inlet tubes of 40mm diameter each, set opposite to each other to supply fuel/air mixture to the plenum and to enhance the mixing process.

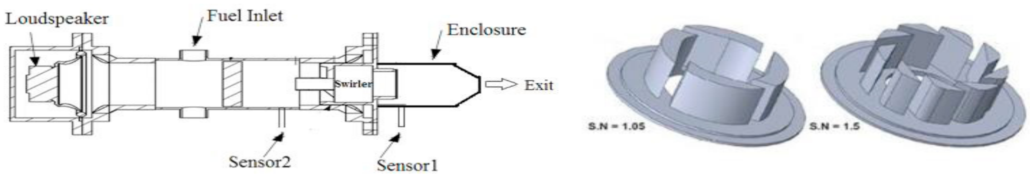


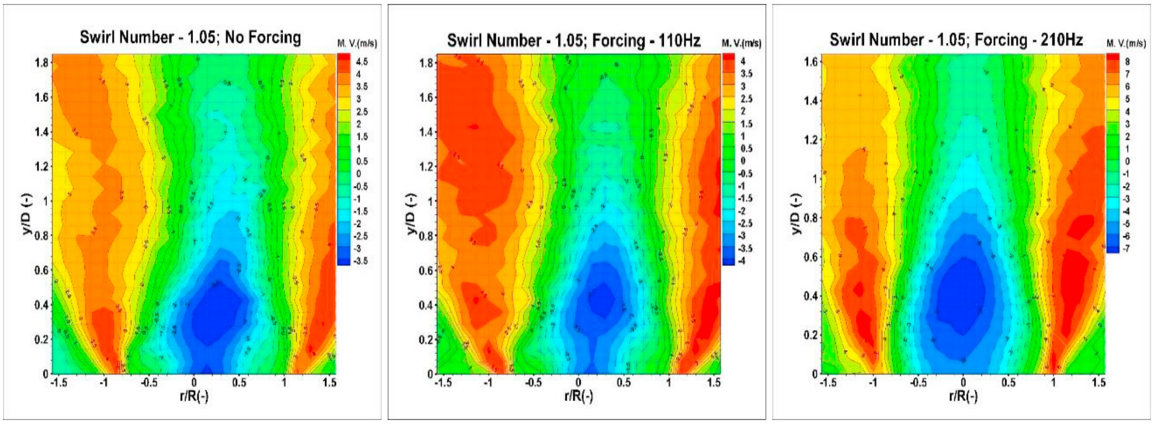

**Figure 1:** Left- Combustion Rig; Right- Two radial swirlers with swirl numbers of 1.05 and 1.5 respectively.

A honeycomb was positioned in the chamber 66mm from the fuel/air supply to straighten the flow and remove large scale perturbation of the flow stream. The injection unit has an 80mm diameter cylindrical section with three pre-swirl vanes attached to a centre shaft which runs throw the main swirl nozzle. Two swirlers of four and nine vanes with a swirl number of 1.05 and 1.50 respectively with an injection nozzle diameter of 28mm were used. The speaker was excited with a sinusoidal signal, generated by a TG503 5MHz Thandar signal generator. The forcing frequency was kept at a range of 0 to 500Hz, as most instabilities are known to occur within this low range of frequency [3]. The velocity fluctuation of the flow field was measured in an isothermal condition using a Flowlite, DANTEC Laser Doppler Anemometry (LDA), with a dedicated Windows Software Package- BSA Flow Software for data acquisition. It was synchronised with DANTEC Dynamics' LDA processors and optical LDA system to provide an integrated velocity measurement through its flexible user's interface. The flame was confined with a 400-mm-long quartz tube of internal diameter of 84 mm flush-mounted with two model 211B kistler pressure transducers within the flame zone. The fuel (methane) and air mass flow rates were varied using a Bronkhorst Hi-tech mass flow regulators with the equivalence ratio kept constant at 0.8. The time series of the dynamic pressure within the flame zone were simultaneously recorded by the two pressure transducers at a sampling frequency of 6500Hz and a run time of 2seconds. They were then processed spectrally to obtain the acoustic modes evolution in the combustor.

## 3. Result

The results present the velocity profiles of the two swirling flows under isothermal conditions to ascertain the effects of the swirl strength and external excitation on the flow profiles. The corresponding effects of these flow evolutions on acoustic dynamics are also examined.

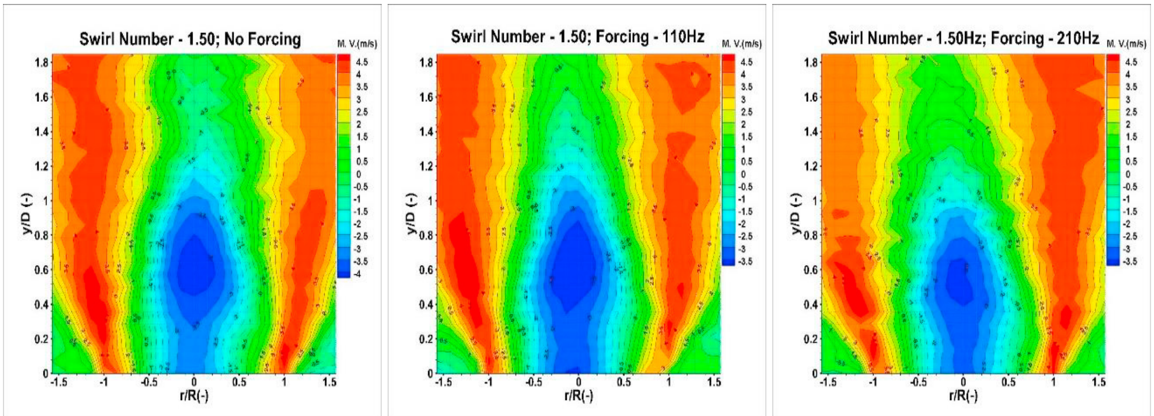
**3.1 Flow Field:** Figure 2a, gives the mean axial velocity profile for the swirl number of 1.05. The velocity profiles show the existence of a well-known flow structure called the central recirculation zone CRZ, which is due to high swirl strength. There is a steep pressure gradient in the radial direction to balance the centrifugal force which leads to a low-pressure core around the centreline [9,17,18], a region with negative velocity, for flame anchorage, efficient and clean combustion. This velocity field ranges from a minimum negative velocity of -3.5m/s to a maximum positive velocity of 4.5m/s located at the high momentum flow region (HMFR) across the shear layers. With the forcing of 110Hz, Figure 2b, the recirculation intensity is increased to -4m/s; the CRZ is elongated with a reduced positive velocity of 4m/s and an increased width of the HFRM with fragmented high-velocity regimes. The forcing frequency of 210Hz, Figure2c, experiences a higher reversed flow mean velocity of -7m/s with enlarged sizes of the velocity regimes. The -6m/s regime circulates close to the dump plane while the –5m/s regime actually penetrates the nozzle annulus.




**(a)** **(b)** **(c)**

**Figure 2:** Velocity profile variations at 1.05 swirl number: (a) Mean velocity of unforced flow (b) Mean velocity of 110Hz forced flow (c) Mean velocity of 210Hz forced flow.

With an increased swirl number to 1.50, Figure 3, the swirl intensity is increased with an elongated CRZ which moves further downstream the flow field. The forcing by 110Hz frequency, Figure 3b, reduces the high mean velocity in the reversed flow to 3.5m/s with an incremental of 0.5m/s of successive regimes to the highest value of 4m/s in the HMFR. The number of flow regimes in the CRZ is also reduced from eight in the unforced flow to seven and remains same with a further increase in forcing frequency to 210Hz , Figure3c, however with different shapes and sizes of the velocity envelopes.

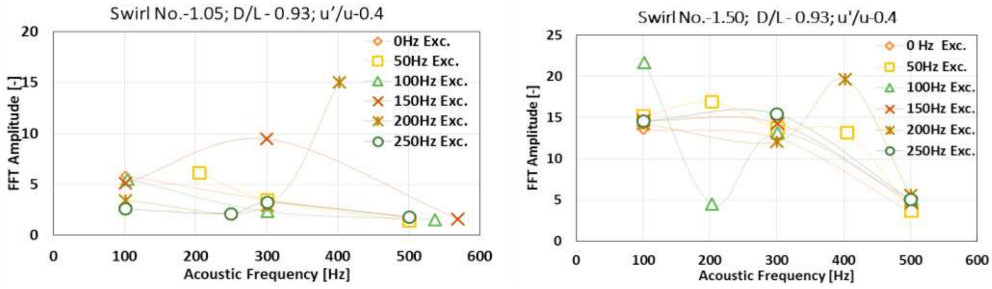



(a) (b) (c)

**Figure 3:** Velocity profile variations of 1.50 swirl number: (a) Mean velocity of unforced flow (b) Mean velocity of 110Hz forced flow (c) Mean velocity of 210Hz forced flow.

These variations in the vortical structures alter the turbulent flame speed [19], with the corresponding impact on both the convective and chemical time scales of the flame processes. In a situation where these characteristic times are of similar magnitude with the acoustic period of the combustor, the mechanisms become self-excited.

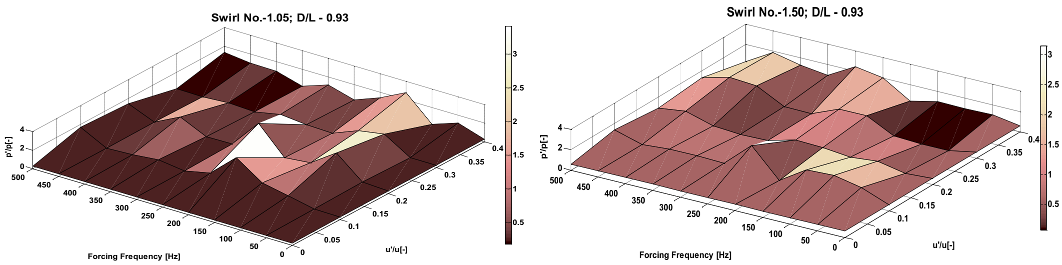
**3.2 Acoustic Field:** Figure 4 shows the evolution of the acoustic modes of the combustor with a change in the swirl strength of the flow field. The magnitude of the power spectrum of the acoustic modes with corresponding acoustic frequencies at different forcing levels indicates the existence of three dominant modes namely 100Hz, 300Hz and 500Hz, which represent the fundamental mode and its harmonics. There is an increase in the magnitude of the dominant acoustic modes as the swirl strength is increased to of 1.50. An increase in acoustic amplitude from 100Hz (5), 300Hz (3) and 500Hz (2) to 100Hz (15), 300Hz (15), and 300Hz (5) were obtained, with an increased swirl number from 1.05 to 1.50. Other lower acoustic modes were ignored as they are attributed to ambient noise. These results show the corresponding influence of the swirl strength and forcing on the acoustic intensity of the combustor.




**(a)** **(b)**

**Figure 4:** Acoustic mode evolutions with a change in swirl strength: (a) S= 1.05 (b) S= 1.50. D/L is the diameter to nozzle length ratio.

Figure 5 gives the normalised dynamic pressure of the combustion chamber for the two swirl conditions at different acoustic forcing frequencies and amplitudes. These values were obtained at the maximum normalised pressure of the time series data of each forcing condition. As indicated by the colour map, the dark portions in Figure 5a with a swirl number of 1.05, shows the reduced pressure ratio of less than 0.5 in most forcing conditions , with only few portions i.e. (250Hz - 0.2u'/u; 300Hz - 0.3u'/u; 150Hz – 0.3u'/u), which have high pressure ratios. These forcing conditions with this high-pressure ratio could be avoided during the operation of the system. With the increase in swirl number to 1.50, the pressure ratio increases significantly with most forcing frequencies and amplitudes.




**(a)** **(b)**

**Figure 5:** Dynamic pressure variations with a change in swirl strength of the flow and forcing :(a) S = 1.05, (b) S= 1.50. D/L is the diameter to nozzle length ratio.

Figure 5b shows the emergence of high-pressure ratios up to 2 in most forcing conditions, with extreme cases at 100-200Hz - 0.2 u'/u and 300Hz - 0.2 u'/u, where they rise above 2.5. Few low-pressure ratios are only observed at higher velocity amplitudes of 0.4 u'/u with a forcing frequency of 150Hz. This is attributed to the saturation of the heat release oscillation resulting in a gradual shift in phase between the oscillating heat release with the dynamic pressure, and the acoustic oscillations are eventually damped. Thus at a swirl number around unity, the acoustic mode is observed to be low but rises significantly as the swirl strength gets to a value of 1.50 at different forcing conditions.

## 4. Conclusion

The combined effect of the swirl and excitation has shown a substantial influence on the flow field with a corresponding impact on the acoustic modes of the combustor. An increase in swirl number increases the swirl intensity especially within the central recirculation zone of the flow field. This changes the turbulence intensity of the flow which alters the heat release fluctuation of the flame zone. The acoustic intensity was also influenced by a combined effect of the swirl number and forcing frequency, as the swirl number around unity maintains a low acoustic modes but becomes intensified as the swirl strength increases to higher values. These results, therefore, demonstrate that the combustor's operating conditions such as the swirl strength and forcing levels could be advantageous in obtaining optimal acoustic modes in the system thus reducing combustion instabilities to its barest. Results of this nature provide information for the design of a control system for the combustor.

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